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RESEARCH **Open Access**

Performance of single-sloped pitched roof cadmium telluride (CdTe) building-integrated photovoltaic system in tropical weather conditions

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Abstract

Background: This paper investigates the performance of a single-sloped pitched roof building-integrated photovoltaic (SSPR-BIPV) system. A typical rural building having a roof area of 60 sq. m is considered for the study. It was observed that the considered roof area could accommodate, nearly 7 kW BIPV system, and on the other side, most buildings seen in Malaysia are of the roof based constructed at different roof pitches. Considering this, a SSPR-BIPV is proposed and analyzed in seven different pitched roofs (the steepness of roof slopes are 15°, 18°, 22°, 30°, 35°, 40°, and 45°) under the tropical weather conditions in Malaysia.

Results and discussion: As per the study constraints, the 7 kW CdTe BIPV under seven different pitched roofs is capable of generating electricity within the range of 9510 to 7710 kWh. Performance ratio and energy losses for seven pitched roofs were identified to be in the range of 74.92 to 76.37% and − 23.63 to − 25.08% respectively. From the results, it is observed that in a BIPV system, as the building roof pitch increases, the energy yields and performance ratios tend to decrease, thereby increasing the overall energy losses.

Conclusion: Hence, this study reveals that there exists a considerable influence of pitched roof over the BIPV performance and suggests using lower roof pitch angles during the installation of BIPV roof especially in the case tropical weather conditions.

Keywords: Solar energy, Photovoltaics, Building-integrated photovoltaics, BIPV, Pitched roof BIPV, Single-sloped roof pitch, Energy performance, Tilt angle

1 Background

Photovoltaics (PV) is the current trend in the energy sector and whose application is emerged into urban and rural infrastructure. They replace the traditional building materials used for the roof, façade, windows, canopy, etc. with building-integrated photovoltaic (BIPV) modules [7, 8, 19]. Like the traditional PV cells, the BIPVs convert incident solar irradiation into the direct current (DC), and this can be used in serving a variety of loads [11]. The generated DC electricity allows the flow of electric charge in only unidirectional. In most cases, this DC electricity can be tapped in storage devices, and the best example is a battery. The generated DC electricity from the BIPV system may serve a few applications such as electric vehicle charging and hydrogen gas production by splitting water molecules using electrolysis. However, to make use of this DC electricity for daily electrical consumption appliances, power conversion devices (PCDs) are to be used. PCDs will convert DC to alternating current (AC). The energy conversion system used for these two systems (PV and BIPV) is almost the same, but the only difference is with the installation procedure adopted [1]. BIPVs are typically installed either on the building roof or façade, making the building itself to be a power-generating station that helps in meeting the increased energy demands of the building sector [34]. Depending upon the building architecture, the installation

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of the BIPV system would vary, for example, flat roof, sloped or pitched roof, façade, and adaptive facades. With the BIPV systems, the scope for attaining the principles of a sustainable building is high, and these will be in terms of electricity consumptions or developing low carbon urban or rural energy system [33]. From this point, it is understood that BIPVs can play an essential role in developing low carbon cities and can be a great asset in meeting the urban or rural energy needs. On the other side, the BIPVs could help in boosting the smart city mission where the need for energy is very high. However, the performance of BIPV system is debatable and it needs integrated thinking of building architecture and the PV technology.

Many researchers have carried out the performance studies on the BIPV system, and their focus was mostly on the BIPV roof or the facades [2, 3, 5, 6, 25–27, 32]. A study by Aristizábal and Páez [5] showed the operational performance of 6 kW BIPV system installed in Colombia (in Bogotá, at 4° 35′ latitude and 2.580 m altitude), and their investigation highlights the AC energy (471,083 kWh/month), final yield (88.6 kWh/kWp-year). In Bellazzi et al. [6], the experimental analysis was carried to understand the performance of BIPV system, and they have highlighted the parameters like operating temperature, global efficiency, and the electric energy. Another study by Medved et al. [27] presented the evaluation methods to understand the thermal response of the BIPV system, which would vary dynamically. They have also investigated the energy performance of most advanced BIPV facade used as building structures. Lee and Yoon [25] used dye-sensitized solar cell (DSSC) for the BIPV applications. In their study, a long-term performance assessment was carried out in both the vertical and inclined configurations. It was highlighted that the performance efficiency of the DSSC BIPV is quite higher in the vertical plane than the sloped plane. The performance of two 12 kWp BIPV systems, one installed on the south façade, and the other as the roof, is investigated in Aelenei et al. [2]. Akata et al. [3] reported the potentials of BIPV in the tropical region of Cameron. As per their assessment, the BIPVs installed on the roofs of the residential apartment can meet a minimum of 3 kW peak energy per day. The performance of BIPV system mounted in a vertical configuration (90° façade) by Lee et al. [26] showed the 1-year measurement. Their results show façade's reference yield, final yield, capture loss, system loss, and performance ratio as 2.15 h/day, 1.52 h/day, 0.49 h/day, 0.14 h/day, and 0.69, respectively. The study of Virtuani and Strepparava [32] presented the simulated performance of two BIPV configurations (south-facing façade at 90°, and roof in 0°). In the performance analysis, the angle of incidence (AOI) method was used to study the reflection losses. On the other side, authors compared two different PV technologies (crystalline silicon and amorphous) for BIPV system performance, and among these, the thin film (amorphous silicon) showed better results as they were benefited in terms of thermal behavior. Kumar et al. [22] presented the performance of 32.7 kW PV system in BAPV and BIPV configurations and compared the energy outputs of three different PV technologies (c-Si, CdTe, and CIS). Among the three PV technologies, CdTe outperforms when compared to CIS and c-Si. The study of Kumar et al. [23] assessed the performance of 5.5 kW BIPV roof and three facades (2.3 kW east and west, and 5.5 kW north). As per the performance results, they perform with an average annual performance ratio between 66.42 and 76.26%.

In all studies mentioned above, the performance of BIPV system is more leaned towards 0° roof and 90° façade. However, in practical conditions, the building architectures have seen drastic changes, and in this context, how to integrate BIPVs to such building architectures is a big question. In the chosen study location, i.e., in Malaysia, most of the buildings that are already constructed or yet be constructed seem to have steepness of roof slopes which is typically referred to as a pitched roof. In the building architecture point of view, the pitched roofs are formed with the rise and run provision, as shown in Fig. 1 [16, 17]. The pitched roof would vary from location to location based on the weather conditions and urban planning regulations. Hence, in such

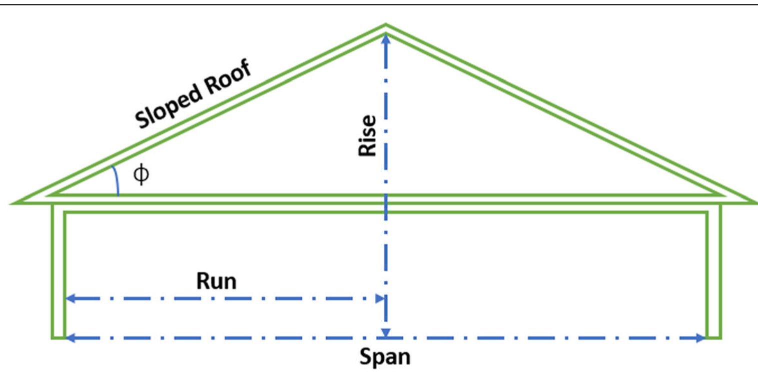

Fig. 1 Schematic view of buildings pitched roof (Φ is the roof angle or roof pitch)

varying pitched roofs, how the BIPV system can be installed and how they perform are the questions which need an extensive investigation. The study of Kumar et al. [21] presented the performance of double-sloped BIPV in tropical weather conditions. Their performance results show the simulated evidence of best performing orientation and roof angles. A study by Lau et al. [24] investigated the performance of BIPV façade, in various roof angles starting from 0 to 90°. They have highlighted the need for temperature control and optimization of BIPV systems, especially in the tropical weathers. Impact of roof angle on the BIPV module temperature is observed, resulting in an overall performance drop. Finally, they have suggested the use of roof angles between 0 and 60°, which inter-help in limiting the module temperature with the wind effect. A study by Alnaser [4] analyzed the performance of 8.64 kW pitched roof (sloped at 25°) BIPV with monitored data of 18 months. The 8.64 kW BIPV performed better with an annual energy generation of 8879 kWh. Another study carried out by Imenes [12] evaluated the real-time performance of BIPV and BAPV systems in Norway. As per the [12], annual specific yields range between 700 and 900 kWh/kWp with 0.85 as an average performance ratio. The above-studied literature suggests the need for investigation of BIPV systems concerning roof angles and how they would perform with different weathers.

Hence, in this paper, the author tries to investigate the performance of BIPV system proposed for the single-sloped rural building, while investigating the effect of pitched roof configuration on the BIPV system performance is given more focus. The primary objective is to study the influence of pitched roof angles on the energy yields, and performance ratios of BIPV system along with other performance indices. The secondary objective is to study the possible energy loss at each pitched roof angle. Energy loss due to the angle of incidence, temperature, and low irradiance are considered at each roof pitch. The manuscript is articulated in three sections: the Section 2 is all about the system configuration and methodology used. In Section 3, the performance results and energy losses discussed, and finally, the concluding points are highlighted in Section 4.

2 Methods

For investigating the energy performance of BIPV concerning the building's roof pitch, a methodology is followed, and it is shown in Fig. 2.

The simulation study is conducted considering the real situation of the building located in the Kuala Pahang region of Malaysia. The location continuously experiences the tropical weather conditions throughout the year. As an initial step, a typical single-sloped pitched roof building profile is executed in SolidWorks. From the building profile, the available area to equip the BIPV modules on the roof surface area was estimated. The capacity of the BIPV is identified using the area to kW rule curve [20]. The available area seems to be around 60 sq. m on the roof surface; hence, approximately around 7 kW BIPV system is proposed (the peak capacity of the BIPV system would vary concerning the BIPV technology chosen). While in performance evaluation, selection of solar irradiance database is an important aspect, here available database from the European Union's

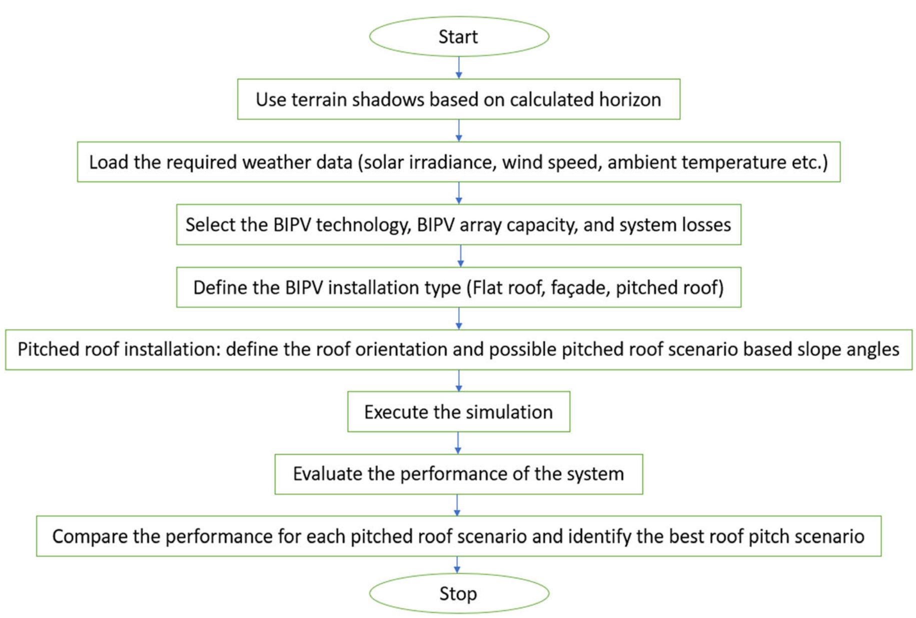

Fig. 2 Simulation procedure

Photovoltaic Geographical Information System (PVGIS) is considered (PVGIS, http://re.jrc.ec.europa.eu/pvgis/) [30]. In some situations, if the solar radiation database is not available, it can be estimated using the empirical relation given in Nwokolo and Julie [29]. The proposed BIPV system is then simulated using the PVGIS simulation tool developed by the Joint Research Centre-European Union considering the location weather parameters and constraints selected for investigating the objective concerning building profile (PVGIS, http://re.jrc.ec.europa.eu/pvgis/; [18, 30]). In Malaysia, most of the residential building seems to be roof based, but in a few cities, we can see the tall and high-rise buildings. If we consider the typical buildings where people are living in urban and rural areas, most of their houses can be grouped under roof based having a single-sloped roof pitch or double-sloped roof pitch [12, 21, 28]. The roof pitch of the buildings could be decided based on the thermal comfort needed by the people living in the building or as per the building roofing standards suggested by the concerned regulatory authority in Malaysia. A draft released by the Department of Standards Malaysia suggests the roofing pitch consideration that would help in installing a roof covering and wall cladding. This report suggests using the pitch angles either less than 18°, between 18° and 22°, and greater than 22° [9, 10]. From the roof installation and covering standards, pitch angles for the rafters are considered, and accordingly, the BIPV array is used to cover the building roof at specified roof pitch angles. However, in the study, an additional four pitched roof angles were considered. With this, a total of seven scenarios that includes 15°, 18°, 22°, 30°, 35°, 40°, and 45° are considered in the performance evaluation of BIPV on a single-sloped roof. The considered single-sloped pitched roof building profile without the BIPV is shown in Fig. 3a, and the same building after covering the roof with BIPV is shown in Fig. 3b. The proposed seven roof pitch scenarios are clearly shown in Fig. 3. Accordingly, the simulation is carried out seven times using the methodology shown in Fig. 2.

Site details and system information are mentioned in Table 1. As our main concentration is to integrate the BIPV onto the single-sloped roof and to make it more convenient, CdTe material-based BIPVs were considered. It is believed that the thin-film BIPV features such as flexible nature and temperature coefficients would favor the solar PV applications in urban or rural infrastructures. Performance modeling equations and performance indices that are adopted in the PVGIS simulation are shown in Table 2.

3 Results and discussion

In this section, the performance results of a single-sloped pitched roof BIPV system under tropical conditions of Malaysia are presented. The examined performance results include the average monthly sum of solar irradiation, average monthly energy productions, the standard deviation in energy production, total energy losses, and performance ratios for seven pitched roof scenarios. In Fig. 4, the calculated horizon for the site location is shown. In Fig. 5, the average monthly sum of solar irradiation received by the BIPV array at various roof pitch angles is shown. In lowered pitched roof scenarios like 15° and 18°, the incident solar irradiance was maximum in April and minimum in December, whereas in rest of the pitched roof scenarios (22°, 30°, 35°, 40°, and 45°) the maximum solar irradiance was experienced in May and minimum in December. In the case of 15° roof pitch scenario, the observed monthly incident solar irradiance on BIPV array was varied between 104 and 173 kWh/sq. m. Similarly, the observed solar irradiance on other roof pitch scenarios is varied between 101 and 172 kWh/sq. m, 96.9 to 171 kWh/sq. m, 88 to 169 kWh/sq. m, 82.1 to 167 kWh/sq. m, 76 to 164 kWh/sq. m, and 69.6 to 160 kWh/sq. m for 18°, 22°, 30°, 35°, 40°, and 45° respectively. From the seven pitched roof scenarios, it is identified that, as the roof pitch angle

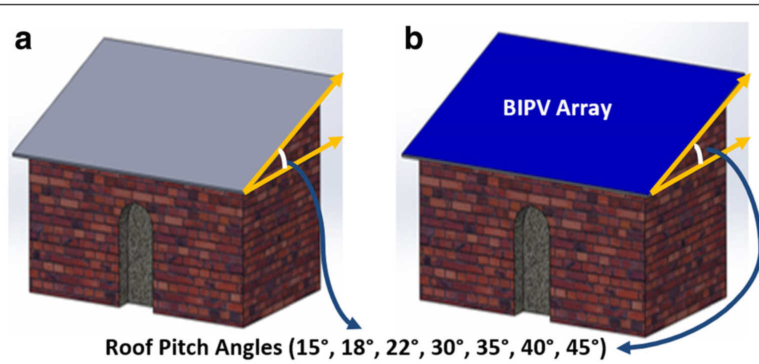

Fig. 3 **a** South-facing single-sloped roof house. **b** South-facing single-sloped roof house with BIPV

Table 1 Study location, area availability for BIPV roof, and pitched roof angles

Description	Name/value
Location name	Kuala Pahang, Malaysia
Latitude	3.5014° N
Longitude	103.4735° E
Elevation	17 m
Available roof area	60 sq. m
BIPV installation type	Single-sloped pitched roof
BIPV peak power	~ 7 kW
BIPV technology	Cadmium telluride (CdTe)
BIPV roof orientation	South facing
Roof pitch variation	15°, 18°, 22°, 30°, 35°, 40°, and 45°

increases, the incident solar irradiance on the BIPV array tends to decrease.

In Fig. 6, the average monthly energy production by the 7 kW BIPV system at considered roof pitch angles is shown. It is observed that the energy generation outputs were decreased as the roof pitch angle increased. The decrease in energy generation between each roof pitch scenario is accountable and quite less in some scenarios. Overall, a small difference is observed between each roof pitch. The monthly energy production by the proposed BIPV array is identified to vary between 544 and 920 kWh, 527 and 916 kWh, 503 and 910 kWh, 449 and 903 kWh, 413 and 892 kWh, 375 and 876 kWh, and 335 and 855 kWh for pitched roof at 15°, 18°, 22°, 30°, 35°, 40°, and 45°, respectively. In lowered pitched roof scenarios like 15° and 18°, maximum energy generation seems to be in April and minimum in December, whereas in the rest of the pitched roof scenarios (22°, 30°, 35°, 40°, and 45°), the maximum energy generation is in May and minimum in December.

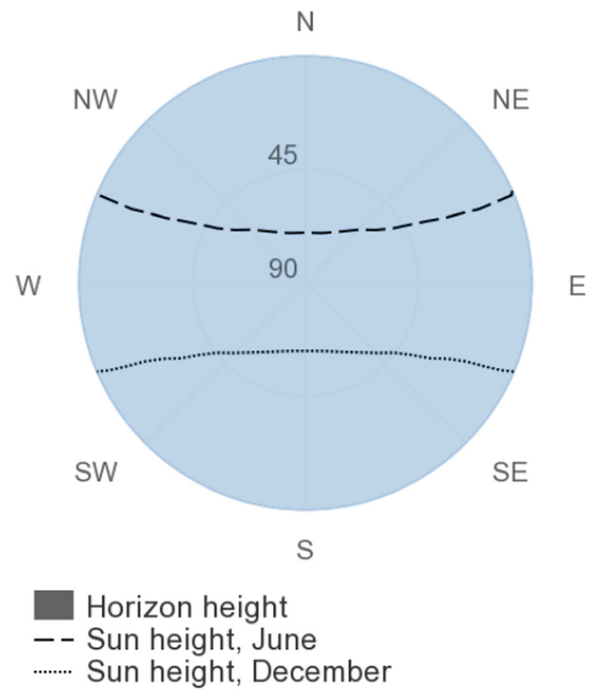

Fig. 4 Outline of the horizon in the site location

The standard deviation of the monthly energy production due to a year to year variability is shown in Fig. 7. Here the possible energy variation from the 7 kW BIPV system at various roof pitch scenarios is examined. The variation is observed to be between 40.1 and 99.2 kWh, 40.2 and 95 kWh, 39.1 and 89.3 kWh, 36.2 and 76.1 kWh, 33.9 and 69.7 kWh, 31.3 and 68.2 kWh, and 29.6 and 66.6 kWh for pitched roof at 15°,

Table 2 Performance modeling equations

Description	Equation	Notations	Reference
Power output	$P(I', T') = I' \times P_{STC}[1 + (t_1 \times ln(I')) + (t_2 \times (ln(I')^2)) + (t_3 \times (T')) + (t_4 \times (T') \times (ln(I'))) + (t_5 \times (T') \times (ln(I')^2)) + (t_6 \times (T')^2)]$	Where, $t_1 = -0.046689$, $t_2 = -0.072844$, $t_3 = -0.002262$, $t_4 = 0.000276$, $t_5 = 0.000159$, and $t_6 = -0.000006$ are the standardized power coefficients, $n = 23.37$, and $n^* = 5.44$ are the standardized temperature coefficients for CdTe PV technology. Where I, I', T', T_m, T_a, P_{STC}, V, $P(I', T')$, E, and PR are the solar irradiance, effective solar irradiance, effective temperature, module temperature, ambient temperature, peak capacity, wind velocity, effective power output, energy, and performance ratio respectively.	(European Solar Test Installation of the Joint Research Centre; http://re.jrc.ec.europa.eu/pvgis/; [13]; [15]; [14]; [21]; [22]; [23], [30])
Effective solar irradiance	$I' = \frac{I}{1000}$		
Effective temperature	$T' = T_m - 25$		
Module temperature	$T_m = T_a + \frac{I}{n + (n^* \times V)}$		
Energy outputs	$E = [P(I', T') \times Time]$		
Performance ratio	$PR = (\frac{E}{I' \times P_{STC}}) \times 100$		

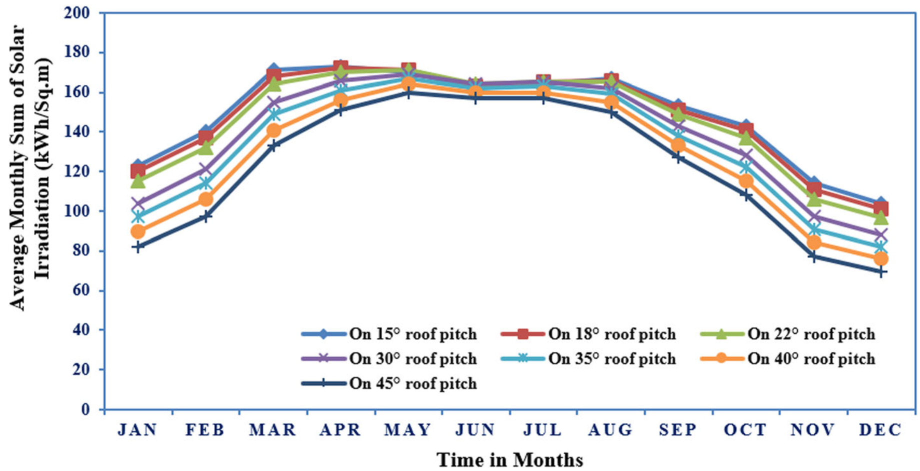

Fig. 5 The average monthly sum of global solar irradiation

18°, 22°, 30°, 35°, 40°, and 45°, respectively. On the other side, in all pitched roof scenarios, energy losses are observed to be in the range of − 23.63 to − 25.08%. It is understood that temperature, the angle of incidence, and low irradiance are the major influencing factors in energy generation. Possible changes in the output energy due to the angle of incidence losses are estimated to be in the range of − 3 to − 4.2%, and temperature and low irradiance losses were identified to be in the range of − 8.6 to − 9.1%. The losses due to reflection at the solar panel surface can be reduced by introducing the antireflective provision using the aluminum oxide and tantalum pentoxide chemicals [31].

Observed performance ratios and energy losses for seven pitched roofs scenarios were identified to be in the range of 74.92 to 76.37% and − 23.63 to − 25.08%. Fig. 8 shows the monthly performance ratios of 7 kW BIPV system at seven pitched roof scenarios. From the investigations, it is observed that performance ratios were slightly varied. The monthly performance ratio of the system is identified to vary between 74.12 and 77.00%, 74.54 and 76.88%, 74.15 and 77.14%, 72.88 and 76.89%, 71.86 and 77.03%, 70.48 and 77.23%, and 68.76 and 77.07% for pitched roof at 15°, 18°, 22°, 30°, 35°, 40°, and 45°, respectively.

In Table 3 summary of the performance, findings are given. The annual in-plane solar irradiation on

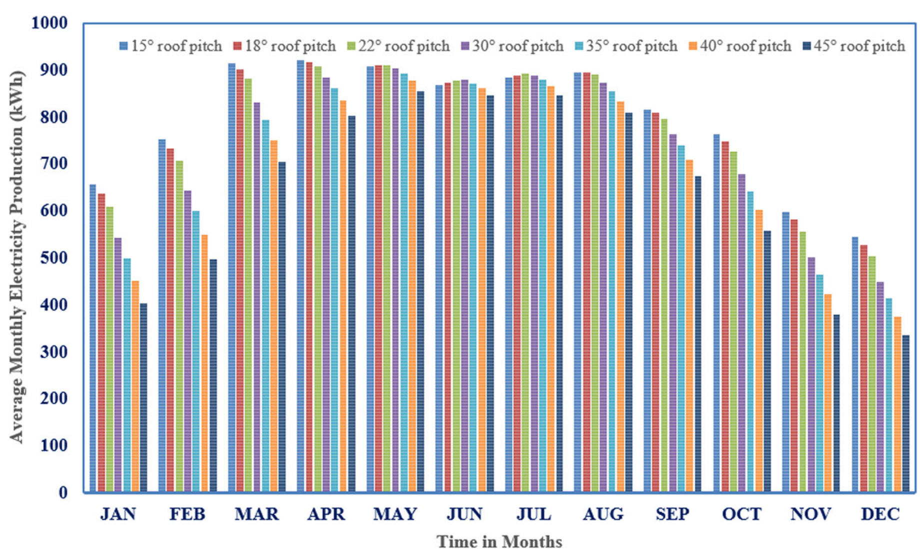

Fig. 6 Average monthly electricity productions

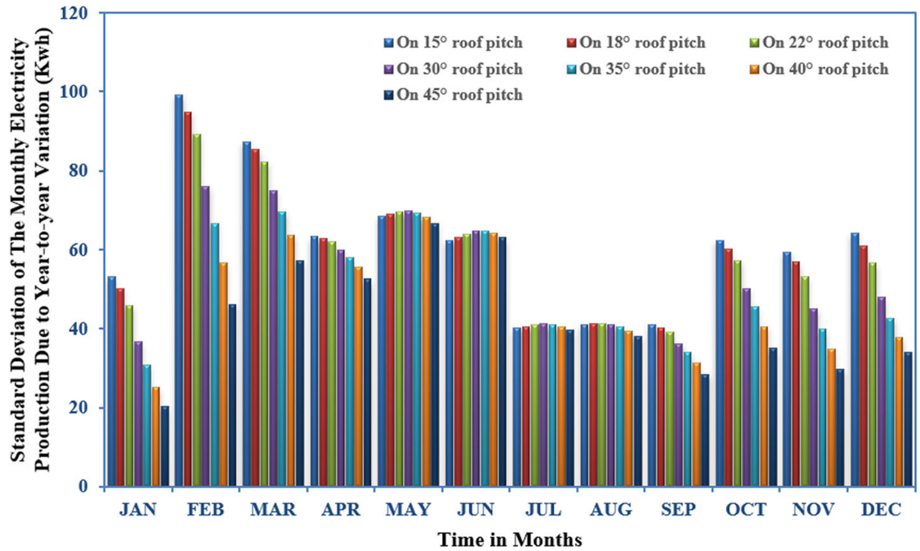

Fig. 7 The standard deviation of monthly electricity production

the BIPV array is observed to be 1780 kWh/sq. m, 1760 kWh/sq. m, 1740 kWh/sq. m, 1660 kWh/sq. m, 1610 kWh/sq. m, 1540 kWh/sq. m, and 1470 kWh/sq. m for the pitched roof at 15°, 18°, 22°, 30°, 35°, 40°, and 45°, respectively. Annual average energy generation under various pitched roofs is observed as 9510 kWh for 15°, 9410 kWh for 18°, 9250 kWh for 22°, 8830 kWh for 30°, 8500 kWh for 35°, 8130 kWh for 40°, and 7710 kWh for 45°. Observed performance ratios for seven pitched roofs were identified to be in the range of 74.92 to 76.37%.

4 Conclusion

In this paper, a study on the performance of cadmium telluride BIPV is presented based on the building's single-sloped roof pitch. From this study, the following conclusions were made:

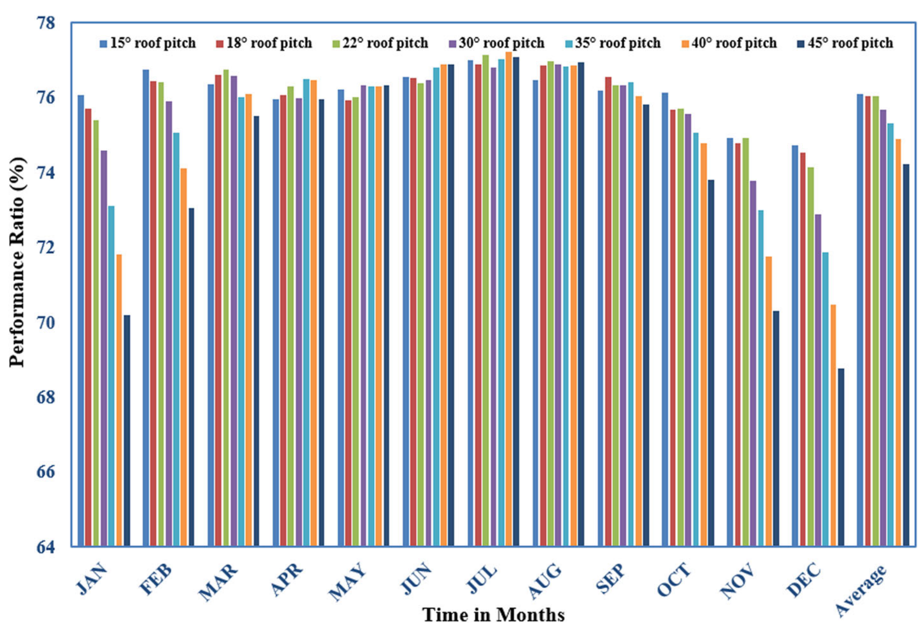

Fig. 8 Performance ratio of pitched roof BIPV power system

Table 3 Summary of the south-facing single-sloped BIPV system performance under seven pitched roof scenarios

Description and the parameters	Output values of the parameters studied in a single-sloped BIPV system						
	15° roof pitch	18° roof pitch	22° roof pitch	30° roof pitch	35° roof pitch	40° roof pitch	45° roof pitch
BIPV capacity as per the available area (kW)	7	7	7	7	7	7	7
In-plane irradiation (kWh/sq. m)	1780	1760	1740	1660	1610	1540	1470
Annual energy production (kWh)	9510	9410	9250	8830	8500	8130	7710
Angle of incidence losses (%)	− 3	− 3	− 3.1	− 3.4	− 3.6	− 3.8	− 4.2
Temperature and low irradiance losses (%)	− 8.6	− 8.6	− 8.6	− 8.7	− 8.8	− 8.9	− 9.1
Total losses (%)	− 23.68	− 23.63	− 24.06	− 24.02	− 24.58	− 24.59	− 25.08
Performance ratio (%)	76.32	76.37	75.94	75.98	75.42	75.41	74.92

- As the roof pitch angle increased, the possible energy generation decreased.
- Lower roof pitch seems to perform better when compared to the higher roof pitch angle.
- Minimal variations are observed in the performance ratios; hence, considering the BIPV building roof construction as per the favoring angle for energy generation is not necessary. However, one can concentrate on the identification of the best roof angle that allows better thermal comfort and structural strength.

This study would give a possibility of decision thinking for the installers to choose the best roof angle for BIPV installation. However, it is suggested to have integrated thinking while considering the BIPV projects.

Abbreviations
AC: Alternating current; AOI: Angle of incidence; BIPV: Building-integrated photovoltaic; CdTe: Cadmium telluride; DC: Direct current; DSSC: Dye-sensitized solar cell; PCDs: Power conversion devices; PR: Performance ratio; PV: Photovoltaics; SSPR-BIPV: Single-sloped pitched roof-building -integrated photovoltaics

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Authors' contributions
The manuscript was the sole contribution of NMK. The author read and approved the final manuscript.

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Availability of data and materials
Data will be made available upon the request. However, author will be sharing all relevant input and output data via the Open Science Framework (osf.io) or other data repository.

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Competing interests
The author declares that he/she has no competing interests.

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